

Astro-quark matter: a challenge facing astroparticle physics

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“ Take a stick of wood with *finite* extent,
one cuts half each day;
it is expected to last out for an *infinitely* long time. ”
— in *Tianxia Pian* by Zhuang Zi [Chuang Tze] (~ 369BC to 286BC)

More than two thousand years ago, a Chinese philosopher, Zhuang Zi, speculated that all of matter in the world are dividable. However, at almost the same time, a Greek philosopher, Demokritos ($\sim 460\text{BC}$ to 370BC), suggested that everything is made up from elements that can not be divided any further, called *atoms* (i.e., in-dividable elements). Now, it is understood in modern physics that atoms are actually dividable because of the detections of electron (discovered by Thomson) and nucleus (by Rutherford), and that the dynamics in an atom is governed by quantum mechanics. In the standard model of particle physics, all of matter are composed of fundamental Fermions, 6 flavors of quarks and 6 flavors of leptons, between which elementary interactions are mediated by gauge bosons. In spite of that, each type of these fundamental particles is supposed to correspond to one of certain vibrational modes of strings (typically $\sim 10^{-33}$ cm) described mathematically in the string theory in order to explain the great discrepancy between the quantum theory and the general relativity. Anyway, it is well recognized that a variety of states of matter exist in different physical conditions (e.g., Fig. 1). *Quark matter* is composed of quarks (and possible gluons) as the dominant degrees of freedom.

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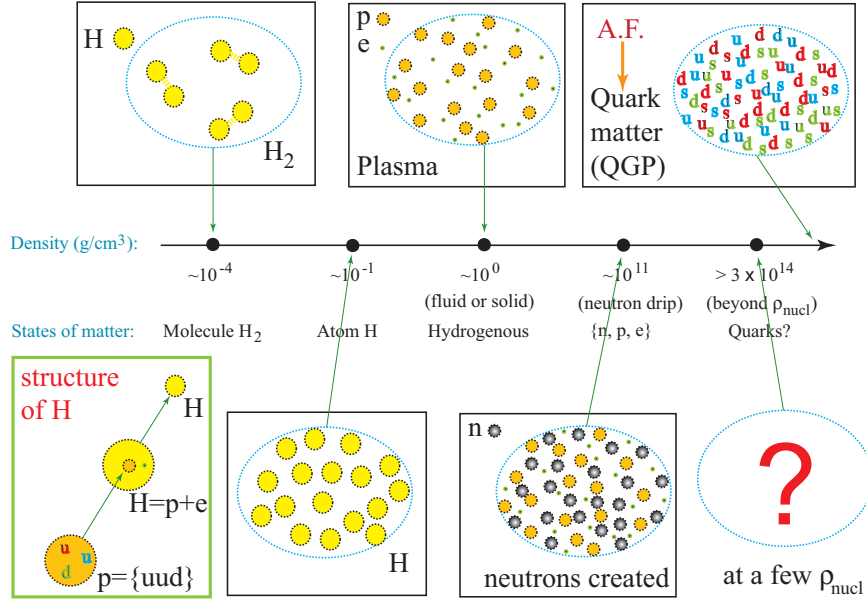


Fig. 1. Density effect dominated phases of matter composed simply of electrons and protons. Temperature effect is negligible here. It is evident that different particle degrees of freedom dominate as the density increases. Note that one could know the microphysics by studying the states of matter at different densities. "A.F.": asymptotic freedom, " ρ_{nuc} ": the nuclear density.

could the strings be made of? The answers to these and other questions related (e.g., the vacuum) would depend on the nature of quark matter, the state of which can be tested by terrestrial experiments as well as astrophysical observations.

Let's introduce briefly the history of quark matter. In the standard model, quantum chromodynamics (QCD) is believed to be the underlying theory of the elementary strong interaction, which has two general properties. For the strong interaction in a small scale (~ 0.1 fm), i.e., in the high energy limit, the interacting particles can be treated as being *asymptotically free*; a perturbation theory of QCD (pQCD) is possible in this case. Whereas in a larger scale (~ 1 fm), i.e., in the low energy regime, the interaction is very strong, which might result in the *color confinement*. The pQCD is not applicable in this scale (the non-perturbative effects are not negligible), and quarks and gluons are confined in hadrons. Nevertheless, in this case, one can still study effectively the color interaction: (i), the lattice formulation (LQCD), with the discretization of space-time and on the base of QCD, provides a non-perturbative framework to compute numerically relations between parameters of the standard model and experimental phenomena; (ii), QCD-based effective models with suitable Lagrangian density could also help us to speculate the features of the low energy QCD; (iii), phenomenological models, which rely on experimental and astrophysics data available at low energy density, are advanced for the phase diagram of QCD (e.g., the states of super-dense hadron and quark matter).

The general features (asymptotic freedom and color confinement) of QCD would result in two distinct *phases* of matter, depicted in the QCD phase diagram in terms of temperature T vs. baryon chemical potential μ_B (or baryon number density). Hadron gas phase locates at the low energy-density limit where both T and μ_B are relatively low, while a new phase called *quark gluon plasma* (QGP) or *quark matter* appears in the other limit when T or μ_B is high although this new state of matter is still not found with certainty yet. It is therefore predicted that there is a kind of phase transition from hadron gas to QGP (or reverse) at critical values of T and μ_B . Actually a deconfinement transition is observed in numerical simulations of LQCD for zero chemical potential $\mu_B = 0$, when $T \rightarrow T_{\text{qcd}} \simeq (150 \sim 180)$ MeV.

Hot quark matter studied via relativistic heavy ion collisions. One way to investigate experimentally the state of quark matter is through collision of two relativistic heavy ions. A kind of matter with asymptotically free quarks and gluons was expected previously, but real experimental results (e.g. RHIC, the relativistic heavy ion collider) indicate a fireball with strong interaction, so-called sQGP¹ (strongly coupled QGP), because of (i) jet quenching (the suppression of one of the two jets produced by a collision pair of energetic quarks or gluons near the edge of the fireball implies a short mean free path of particle in the bulk matter formed) and (ii) elliptic flow (successful hydrodynamics computations for the spatially anisotropic flow shows that the bulk matter could be well approximated by perfect fluid, i.e., zero mean free path, in case of low transverse momentum). Besides, an interesting form of matter, the color glass condensate (a term “glasma” is then coined), is argued to occur before reaching an equilibrium state of the fireball (several typical time scales are comparable at that time)².

The sQGP matter is surely a new state with energy densities more than ten nuclear density and at temperatures of particle kinematic energy of ~ 200 MeV. It is worth noting that the composed ingredients in the sQGP is quarks and gluons, which is not confined in hadrons, but the interaction between these particles is very strong. As argued by Csorgo³ for the Pb+Pb collisions at CERN SPS (super proton synchrotron), this new form of matter created is in principle not QGP theoretically predicted, but is actually quark matter with effective degrees of freedom to be the massive (dressed) constituent quarks instead of almost massless quarks and gluons. The future Brookhaven RHIC and CERN LHC (the large hadron collider) programs will certainly improve our understanding of this kind of quark matter.

Anyway, how can we test further our theoretical view points on sQGP by other experiments? What could be the astrophysical implications of sQGP?

Cold quark matter studied astrophysically? Another way to do is via observing astrophysical appearances as well as implications of quark matter. All the possible quark matter residual from astrophysical processes is cold though it may be hot initially (e.g., during the early Universe).

Cold quark matter is another story. Extremely dense quark matter could certainly be regarded as ideal Fermi gas due to the asymptotic freedom. However,

should astrophysical quark matter at a few nuclear densities be asymptotically dense? In fact, it appears that the highly degenerate Fermi surface should be unstable to form Cooper quark pairs, condensed in momentum space, around the surface when weak attraction between quarks is introduced. A novel state, which is similar to the electric superconductivity, is then speculated, called color superconductivity (CSC), for cold baryon matter at a few nuclear densities⁴. A state of two-flavor color superconductor (2SC) may occur at lower density, while a color-flavor locked (CFL) phase would exist at higher density.

What if the mean free path of quarks in cold quark matter is *very short* (i.e., the matter is also strongly coupled)? This is an interesting question necessary to be raised and answered after discovering strong interaction in the hot quark matter.

Actually, based on possible astrophysical features detected, a state of solid quark matter was conjectured five years ago, just before inventing the abbreviation of “sQGP”, and the author proposed more realistically that quark clusters (i.e., quarks are condensed in *position* space rather than in momentum space) could be essential for the *normal* solid state⁵. This idea would be natural since a short mean free path may favor positional condensation of particles. As illustrated in Fig. 2, in different locations of the QCD phase-diagram, the vacuum would have different features and is thus classified into two types: the perturbative-QCD (pQCD) vacuum and nonperturbative-QCD (QCD) vacuum. The coupling is weak in the former, but is strong in the latter. Quark-antiquark (and gluons) condensations occur in QCD vacuum (i.e., the expected value of $\langle q\bar{q} \rangle \neq 0$), but not in pQCD vacuum. The chiral symmetry is spontaneously broken in the case that the vacuum is changed from pQCD to QCD vacuums, and (bare) quarks become then massive constituent ones (dressed quarks). This theoretical points are consistent with the solid quark matter speculation since there is no observation that the quark deconfinement and the chiral symmetry restoration should occur simultaneously. Besides, based on the effective models, the rigidity of CSC quark matter could not be negligible if the gap parameter modulates periodically (i.e., the translational invariance is thus broken), and the shear moduli of this crystalline *super*-solid state could be as high as 20 to 1000 times larger than those of neutron star crusts⁶. It could be interesting to observationally distinguish between and search evidence for possible normal-solid and super-solid states although the latter seems to be more robust than the former from a purely theoretical point of view.

We will try an effort to review briefly the astrophysical quark matter in the next section. The previous short reviews^{7,8} could also be valuable for some details.

2. Quark matter in astrophysics

There could be mostly three forms of astrophysical quark matter, i.e., appearing in the early Universe, in compact stars, and as cosmic rays.

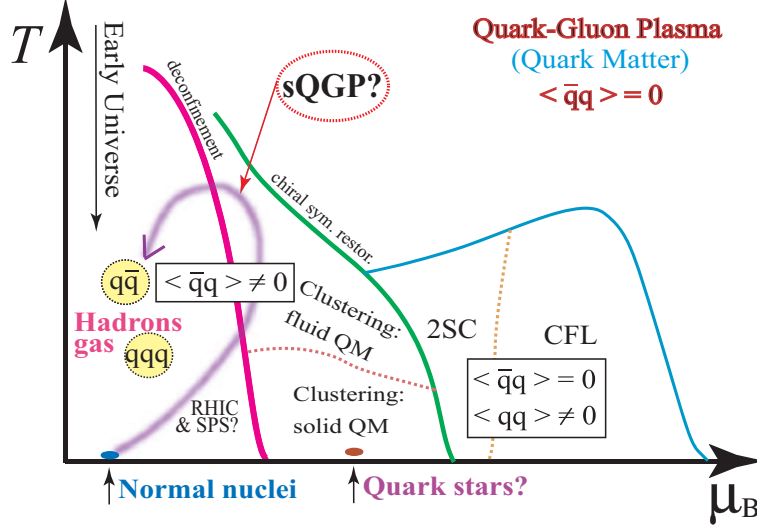


Fig. 2. Schematic illustration of QCD phase diagram speculated in astrophysics.

2.1. Cosmic QCD phase transition

The symmetry in high-temperature (high- T) is much larger than that in low- T , the vacuum could then undergo various phase-transitions in case of symmetry breaking when the Universe cooled as it expanded. One of the transitions relevant to astro-quark matter is a QCD transition in the early Universe. In the radiation-dominated universe, whose space-time is described by Robertson-Walker metric, the temperature can be well approximated simply by $T \simeq 1 \text{ MeV}/\sqrt{t}$, with the cosmic age t in seconds. According to LQCD simulations for case of zero chemical potential, a quark-hadron phase-transition (QHPT, or QCD transition) took place at temperature $T_{\text{qcd}} \simeq (100 \sim 200) \text{ MeV}$ when the cosmic age was $t_{\text{qcd}} \simeq 10^{-5} \text{ s}$.

The cosmic QHPT is very close to an equilibrium process, since the relaxation time scale of color interaction, $\sim 1 \text{ fm}/c \sim 10^{-23} \text{ s}$, is much smaller than the time interval $t_{\text{qcd}} \sim 10^{-5} \text{ s}$ in which the cosmic thermodynamical variables and expanding-dynamical curvature can change significantly (see Ref. 9 for a general review). The key uncertainty factor is the order of QHPT, on which several astrophysical implications depend (see next three paragraphs). A first-order transition may proceed through bubble nucleation. The hadronic bubbles grow, release latent energy, and could collide with others when they are larger enough (i.e., bubbles with hadron gas grew until they merge and filled up the whole universe in the end of QHPT). The horizon radius at that time is $R_h \sim ct_{\text{qcd}} \sim 10 \text{ km}$. However, the typical separation between bubbles, D_b , could be much smaller than the horizon radius, that is only $D_b \sim 10^{-6} R_h \sim 1 \text{ cm}$ according to lattice QCD calculations where the bubble surface tension and latent heat are included.

The cosmic QHPT may have many astrophysical consequences which would test

the physical process in turn. Big-bang nucleosynthesis (BBN) predicts the abundances of the light elements (D, ^3He , ^4He , and ^7Li) synthesized at cosmic age of $\sim 10^3$ s, which are observation-tested spanning *nine* orders of magnitude (number ratios: from $^4\text{He}/\text{H} \sim 0.08$ down to $^7\text{Li}/\text{H} \sim 10^{-10}$). However, the initial physical conditions for BBN should be set by this QHPT. For instance, the inhomogeneities of temperature and baryon numbers during bubble nucleation may affect the abundances synthesized, which may clear the possible inconsistency of the light element abundances with the CMB measurements¹⁰. In this sense, BBN offers then a reliable probe of QHPT. As a result, this study could provide a better determination of the baryonic density in the universe.

The formation of quark nuggets could be another probable consequence. Towards the end of the QHPT, baryon-enriched quark droplets shrank, and might remain finally to play the role of dark matter¹¹. Quark droplets with strangeness are conjectured to be absolutely stable, and the residual quark nuggets could then probably be composed of strange quark matter with high baryon density. Can we detect such quark nuggets? This could be a meaningful project to be done, both experimentally and theoretically, in the future.

There could be other relics of cosmic QHPT. A very interesting issue is to study the bubble collisions which may be responsible to the generation of gravitational waves¹¹. Seed magnetic fields could be produced by currents on the bubble surface¹².

2.2. *Quark matter and pulsars*

Although one may conventionally think that pulsars are ‘normal’ neutron stars, it is still an open issue whether pulsar-like stars are neutron or quark stars^{13,14,15}, as no convincing work, either theoretical from first principles or observational, has confirmed Baade-Zwicky’s original idea that supernovae produce neutron stars.

2.2.1. *Historical notes on pulsars, neutron stars, and quark stars*

Soon after the Fermi-Dirac form (in 1926) of statistical mechanics was proposed for particles which obey Pauli’s exclusion principle (in 1925), it is Fowler (in 1926) who recognized that the electron degeneracy pressure can balance for those stars, white dwarfs discovered by astronomers in 1914. Only two further steps (the state equation of a completely degenerate gas and numerically calculating the hydrostatic equilibrium with the state equation) are needed to pass from Fowler’s discovery¹⁶, that were then carried out by Chandrasekhar (in 1931) who found a unique mass (the mass limit of white dwarfs). What if the mass of a star supported by electron degenerate pressure is greater than the Chandrasekhar limit? Landau speculated a state of matter, the density of which “becomes so great that atomic nuclei come in close contact, forming one *gigantic nucleus*” in 1932. A star composed dominantly of such matter is called a “neutron” star, and Baade and Zwicky even suggested in 1934 that neutron stars could be born after supernovae. A direct observational

evidence, proposed by Gold in 1968, is detecting pulsed radio beams (pulsars) due to the lighthouse effect of spinning neutron stars, although pulsars were supposed to “be associated with oscillation of white dwarfs or neutron stars¹⁷”.

However, neutrons and protons are in fact *not* structureless point-like particles although they were thought to be elementary particles in 1930s; they (and other hadrons) are composed of *quarks* proposed by Gell-Mann and Zweig, respectively, in 1964. The quark model for hadrons developed effectively in 1960s, and Ivanenko & Kurdgelaidze¹⁸ began to suggest a quarkian core in a massive neutron star. Itoh¹⁹ even considered 3-flavor ($\{u,d,s\}$) *full* quark stars (now called *strange* quark stars), with calculation of their hydrostatic equilibrium. The speculated quark stars could really exist if bulk strange quark matter is most stable¹¹. Haensel, Zdunik & Schaeffer²⁰ and Alcock, Farhi & Olinto²¹ then modelled strange stars, and found that these quark stars can also have typical masses of $\sim (1 - 2)M_{\odot}$ and radii of ~ 10 km, that means that *the pulsar-like stars believed previously to be neutron stars might actually be quark stars*.

How to distinguish observationally quark stars from neutron stars? Alcock et al.²¹ thought that (1) a strange quark star would accrete inter-stellar matter, and then a crust would form, wrapping the strange quark star, and (2) a bare strange star can not manifest itself as a radio pulsar because of being unable to generate a magnetosphere. This view was criticized by Xu & Qiao²², who addressed that these two points are theoretically unsuitable, and that *bare* strange quark stars (i.e., without crusts) are welcome for astronomers to understand observation. A new window to distinguish between neutron and quark stars is then opened since there are striking differences between the exotic quark surfaces of bare quark stars and the normal matter surfaces of neutron stars. With regard to the possible methods to identify quark stars in literatures, hard evidence may be obtained by noting the surface differences since the other avenues are subject to many complex nuclear and/or particle physics processes that are poorly known.

It is really a non-perturbative task to understand the QCD phase diagram, to which a vast range of fundamental physics problems are related. The state of matter in pulsar-like stars is yet not determined. Nevertheless, we would like to summarize various speculations about the nature of pulsars in Fig. 3.

2.2.2. Observational hints that pulsar-like stars could be quark stars

Although quark stars seem to be ‘easily’ ruled out from time to time in the literatures (similar to the case of one’s refraining from smoking), we would like to address possible evidence for them since this is still an unsolved physical and astrophysical problem mixed with a variety of research subjects.

Magnetospheric and thermal emission features: bare quark surface? The RS-type vacuum gap model²³, with an “user friendly” nature, is popular and successful in explaining the radiative behaviors of radio pulsars, which can only work in strict conditions: strong magnetic field and low temperature on surface of pulsars with

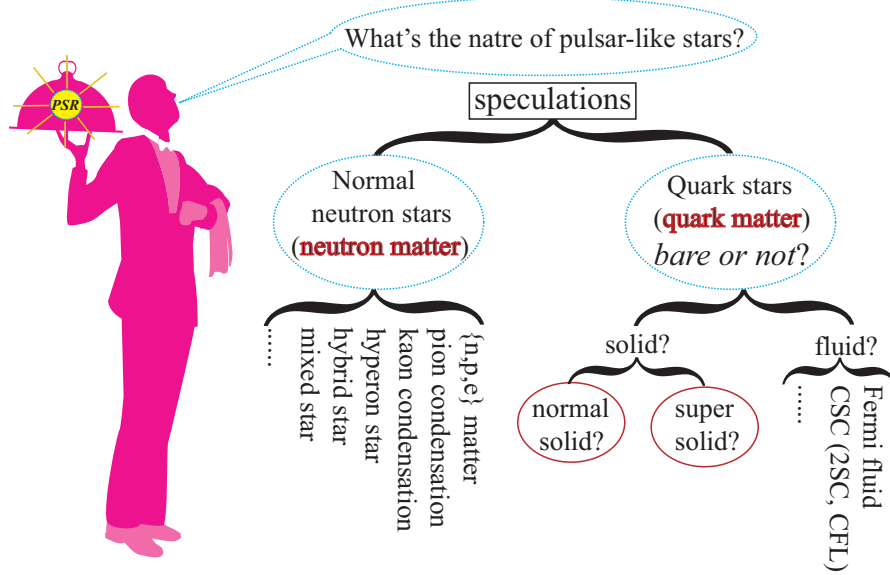


Fig. 3. We are still not sure about pulsar's real internal structure because of the uncertainty of the state of matter at supra-nuclear densities. A variety of states have then been speculated for the nature of pulsar-like stars, which could be classified into two categories: neutron (or nuclear) matter (normal neutron stars) and quark matter (quark stars).

$\Omega \cdot \mathbf{B} < 0$. This binding energy could be completely solved for any $\Omega \cdot \mathbf{B}$ if radio pulsars are bare quark stars^{22,24}. Drifting subpulses²⁵ and microstructures could be strong evidence for RS-type sparking on polar caps, and further more, the bi-drifting phenomena²⁶ could only be understood in a bare quark star model. Additionally, the bare quark surface could also help to explain a few other observations. Only a layer of degenerated electrons in strong magnetic fields on bare quark surface, which can naturally reproduce non-atomic spectra²⁷ though atomic features were predicted in normal neutron star models long before the observations. The absorption lines of several X-ray sources (e.g., 1E1207 and SGR1806) could originate from transition between Landau levels of electrons²⁸. Besides both magnetospheric and thermal emission features, the quark surface may help to alleviate the current difficulties in reproducing two kinds of astronomical bursts which are challenging today's astrophysicists to find realistic explosive mechanisms. Because of chromatic confinement (the photon luminosity of a quark surface is then not limited by the Eddington limit), bare quark stars could create a lepton-dominated fireball^{29,30} which could push the overlying matter away through photon-electron scattering with energy as much as $\sim 10^{51}$ erg for successful supernovae³¹. Asymmetric explosion in such a way may naturally result in long-soft γ -ray bursts and in kicks on quark stars³².

Mass-radius relation: low-mass quark stars? The striking difference between the mass-radius relations¹⁴ of normal neutron stars and of (bare) quark stars is thought

to be useful for identifying quark stars, and yet it is worth paying attention to *low-mass* quark stars²⁹ since quark and neutron stars with similar maximum masses can hardly be distinguished observationally. Actually, there may be some observational hints of low-mass pulsar-like stars, which include the spin and polarization behaviors³³ of PSR 1937+21, the peculiar timing behavior²⁹ of 1E1207, no-detection of gravitational waves from radio pulsars³⁴, and small polar cap area³⁵ of PSR B0943+10. The detected small thermal area³⁶ (*if* being global) of central compact objects may reflect their low masses too. Solar-mass and low-mass quark stars may form in different channels: core-collapse explosion for the former and AIC (accretion-induced collapse) of white dwarfs for the latter. The latter could also be possibly the residue of cosmic QCD phase separation in the early Universe.

Evidence for solid quark matter? Based on a variety of observational features, a solid state of cold quark matter was conjectured⁵, which could be allowed in the regime of QCD. A star-quake occurs as strain energy develops in an evolving solid star with rigidity, which can naturally result at least in two observable phenomena: bursts due to energy release and swift/slow spin jumps due to change of inertia momentum. As noted previously⁷, two kinds of factors could result in the development of stress. (i) As a quark star cools (even spinning constantly), changing state of matter may cause a development of anisotropic pressure distributed inside a solid matter. Such matter cannot be well approximated by perfect fluid, and the equation governing star's gravitational equilibrium should then not be the TOV equation. For stars being spherically symmetric, one can introduce the difference between radial and tangential pressures, Δ . Change of Δ would lead to no-conservation of stellar volume. Quakes in this *bulk-variable* case could be very strong and may explain the superflares of soft γ -ray repeaters³⁷. (ii) An uniform fluid star would keep the Maclaurin figure, and the eccentricity decreases as a star spins down. However, for a solid star, the shear stress would prevent the star from decreasing eccentricity during spindown, and *bulk-invariable* force develops then. As demonstrated in Fig. 4, a glitch occurs too as the stress releases. Both bulk-invariable and bulk-variable forces could result in decreases of moment of inertia, and therefore in pulsar glitches. These two kinds of forces could trigger normal glitches³⁸ if they are relatively stronger than a critical stress, but might only conduce to slow glitches³⁹ if weaker.

Others. (i). The mass of quark star could be low due to self-confinement, but also be high due to the high incompressibility of solid quark matter. Stellar models for *non-perfect* fluid matter would then be necessary to explain pulsar's mass $\gtrsim 2M_{\odot}$ (e.g., the mass⁴⁰ of PSR J0751+1807). (ii). Solid quark stars might sustain maximum dimensionless quadrupoles up to a few times 10^{-4} , being much higher than that of neutron stars⁴¹, and their gravitational waves are then stronger. However, the gravitational radiation from low-mass solid quark stars, even with maximum quadrupoles, should be negligible³⁴, and no such a signal could thus be found in the data from the fourth LIGO science run⁴². (iii). The SGR-like superflares in distant galaxies could be the dominated mechanism for short-hard γ -ray bursts since the released energy via such giant quakes could be as high as $\sim 10^{48}$ ergs³⁷.

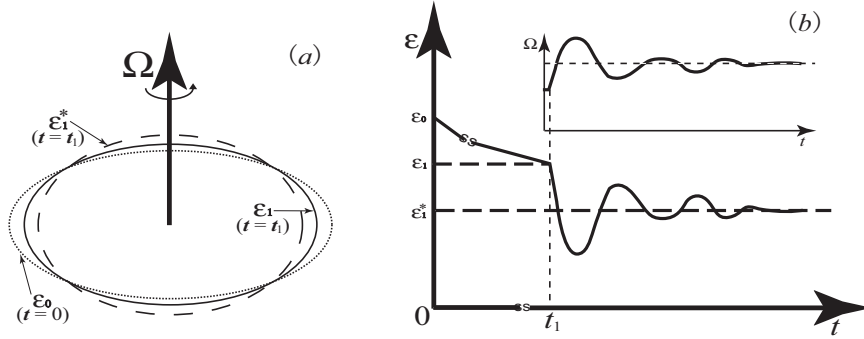


Fig. 4. An illustration of bulk-invariable force induced quake of a solid quark star. The Maclaurin figure determines the eccentricities of ϵ_0 and ϵ_1^* . A star-quake with real eccentricity ϵ_1 occurs at time t_1 . The ϵ -oscillation damps quickly due to high effective-viscosity during a real quake process.

2.2.3. To identify a quark star in the future?

Four ways to test quark star model were recorded in an “arXiv.org” paper (astro-ph/0410652), which was published two years later⁴³. I will follow these points because I think they are *not* behind the times. (i). Dust emission around pulsar-like stars. Disks around quark stars are suggested although the details are still not yet clear. Sub-millimeter emission at temperature ~ 0.1 eV could be expected⁴³, and the Spitzer detection⁴⁴ could be related. (ii). Determination the radii of distant pulsar-like stars. We can hardly conclude a detection of pulsar-like star with radius $\lesssim 5$ km through bolometric observations because of the debate: are the detected thermal components global or local? Nonetheless, future X-ray interference telescopes (e.g., *MAXIM*) may make it possible to constrain real stellar radii. (iii) Gravitational wave detection. Gravitational wave emission associated with the energetic superflares of SGRs may be gathered from the LIGO data⁴⁵, and an upper limit⁴⁶ of 7.7×10^{46} erg for the 92.5 Hz QPO of SGR 1806-20 had been put. However, significant high-frequency ($\sim 10^{(3-7)}$ Hz) gravitational waves during the initial spikes of superflares may be radiated since most of the photon emission is also radiated initially ($\lesssim 1$ ms). (iv). Searching for sub-millisecond pulsars. Normal neutron stars can not spin at period $\lesssim 0.5$ ms, but low-mass bare quark stars can²⁹, even $\lesssim 0.1$ ms. It is then a very clear evidence for quark stars if we could detect sub-millisecond pulsars by advanced radio telescope (e.g., the “FAST”) in the future.

Quark stars with companions of white dwarfs or quark planets are expected^{29,34}. A planet around a white dwarf could be a quark planet if no thermal emission predicted for normal planets is detected. Precise pulsar timing and advanced IR/sub-millimeter detecting are then necessary to test these ideas.

2.2.4. Quark stars v.s. neutron stars

At this stage of study, most the observations could be principally understood in both neutron and quark star models. However, there are some features which have not been extensively studied. A comparison between neutron and quark star models is summarized in Table 1. It seems that the neutron star model is more questionable.

Table 1. Neutron stars vs. Quark stars: to explain the observational features of pulsar-like stars in these two kinds of models.

	Phenomena observed	Normal neutron stars	(solid) quark stars	Note
Radio pulsars:	magnetospheric emission	ok?	ok?	e^\pm plasma
	normal glitch	vortex (un)pinning	star-quake	to be tested
	slow glitch	???	in low-mass quark star	not in NS model
	(bi)-drifting sub-pulses	binding??	binding!	surface condition
	(free) precession	damped?	no damping	rigid or not
AXPs/SGRs*:	timing noise	high in msPSRs?	solar or low mass	random torque
	energy source	B-field	gravity & strain	magnetar?
	burst with glitch 10^{-6}	?	AISq*	sometimes
CCOs*:	super-flare	high-B magnetar?	giant-quake?	
	age discrepancy	?	quark star with fossil disk	
DTNs*:	erratic timing	?	torque by disk	
	non-atomic feature	high B or Z ?	bare quark stars!	
<i>Thermal radii</i>	why small?	polar cap?	low-mass quark stars	local or global
APXPs*:	ADmsPSRs*	ok?	low-mass quark star?	spin up & down
XRBS*:	bursts	nuclear power	crusted quark star?	
Sub-msPSR*:	spuper-Kepler spin	no!	possible	prediction (QS)
Others:	supernova	ν -driven??	γ -driven?	not successful
	MACHOs*	?	(low-mass) quark stars?	
	UHECRs*	?	strangelets?	

*AXPs/SGRs: anomalous X-ray pulsars/soft γ -ray repeaters; CCOs: compact central objects; DTNs: dim thermal “neutron stars”; APXPs: accretion-powered X-ray pulsars; XRBS: X-ray bursters; Sub-msPSRs: sub-millisecond pulsars; MACHOs: massive compact halo objects; UHECRs: ultra-high energy cosmic rays; AISq: accretion-induced star-quake.

Let’s choose one, discussed previously⁴³, in Table 1. The timing noise is strongest in AXPs/SGRs (slowest rotators), but is weakest in millisecond pulsars (slowest rotators); the noise level of normal pulsars (moderate rotators) is in between those two. This is strange in the neutron star model since the torque variability increases with Reynolds numbers (and thus spin frequency)⁴⁷. While, this observation could be nature in the quark star model: the mass of most of millisecond pulsars could be $\ll 1M_\odot$, and there should be debris disks around AXPs/SGRs.

2.3. Quark nuggets in cosmic rays

Two scenarios of quark nuggets in cosmic rays are discussed in the literatures: (i) to overcome the difficulty^{48,49} beyond the GZK cutoff of the ultra-high energy cosmic rays with energy $> 10^{19}$ eV, and (ii) several exotic cosmic ray events reported

by balloon and mountain experiments to be possible candidates of strangelets (the doubly charged event⁵⁰ detected by the AMS experiment in space could be a special one). Quark nuggets could be produced in the cosmic QCD transition, might originate from the collisions of two quark stars, and could also be ejected by supernova explosions. It is worth noting that the massive compact halo objects (MACHOs) discovered through gravitational microlensing⁵¹ could probably also be low-mass quark stars formed by evolved stars, rather than quark nuggets born during the QHPT⁵², if pulsar-like stars are actually quark stars.

2.4. *Others*

(i). Quark matter residues from the cosmic QCD separation could be candidate of cold dark matter¹¹. (ii). Quark molecular dynamics (qMD) develops to test the phenomenological interaction-models for hot sQGP. An extrapolation of this to studying cold quark matter may result in a solid state⁸. (iii). What if a quark nugget collides with or goes through the Earth? It is interesting to see the seismic⁵³ or other responses of such compact object from space.

3. Conclusions

The idea of quark matter has great implications in astrophysics. Both perturbative and nonperturbative QCD studies would be involved in understanding the QCD phase diagram, and the hot sQGP discovered in RHIC could surely help to understand cold quark matter in astrophysics.

It is a pity that the real state of matter in pulsar-like stars is still not determined confidently because of the uncertainty about cold matter at supranuclear density, even 40 years after the discovery of pulsar. Nuclear matter (related to *neutron stars*) is one of the speculations for the inner constitution of pulsars even from the Landau's time more than 70 years ago, but quark matter (related to *quark stars*) is an alternative due to the fact of asymptotic freedom of interaction between quarks as the standard model of particle physics develops since 1960s. Possible observational evidence/hints that pulsar-like stars could be quark stars are summarized, with the inclusion of achievable clear evidence for quark stars in the future. A solid state of cold quark matter is emphasized, and I focused on the work of my group and feel sorry for neglecting many interesting references due to the page limit.

There are actually three ways to study QCD phases: lattice QCD simulations, effective QCD models, and phenomenological models. A combined study of these three should be *very* necessary to know the real QCD diagram.

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